Lunar Regolith Mobility and Excavation Modeling

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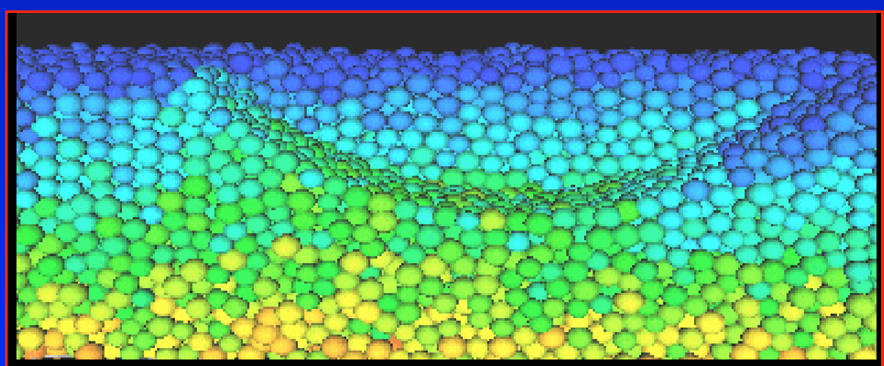
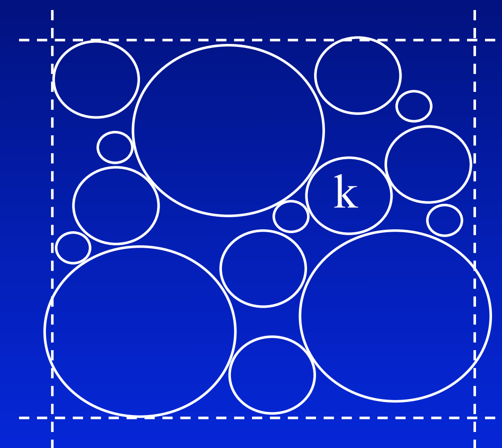
Motivation

- **To describe lunar soil mechanical behavior and describe complex machine/ soil behavior we are developing a physics-based discrete element method (DEM) simulation capability**

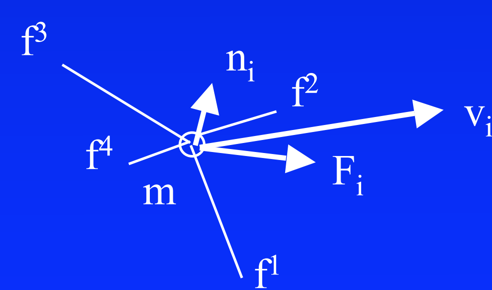


Evolving slip plane failure mechanisms between groups of particles

Discrete Particle System



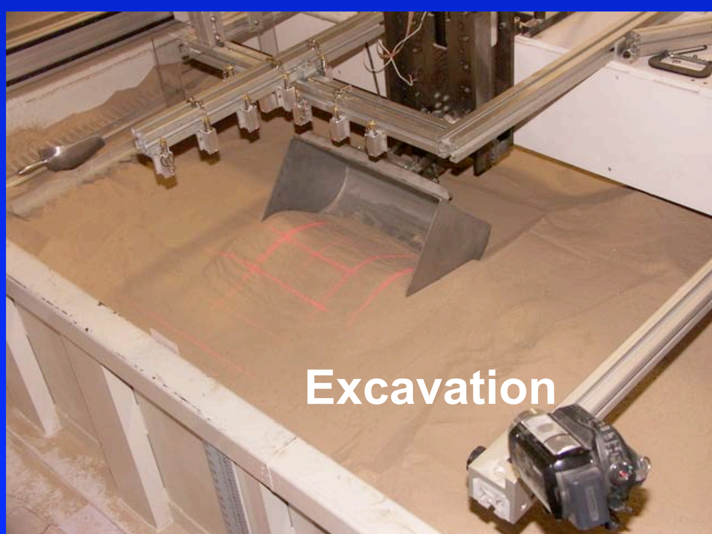
Forces Acting on Particle k

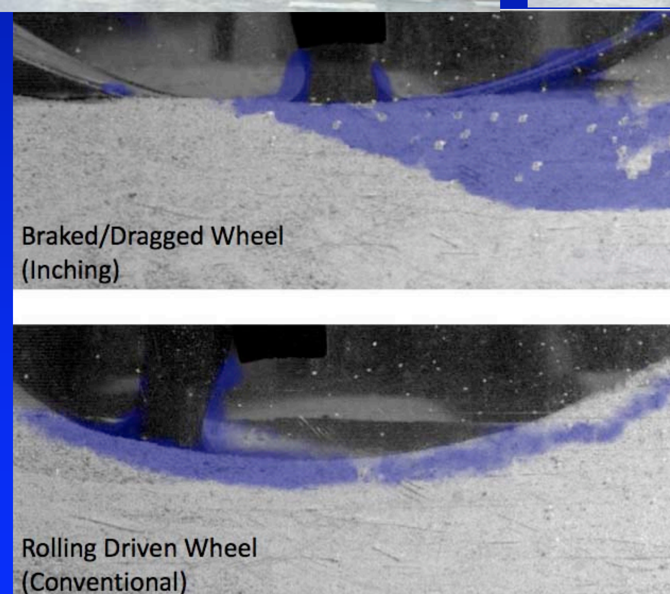


Importance for Science and Engineering

- Large deformation and progressive failure of granular media are most accurately simulated using DEM
- Design next generation equipment
- Relate Earth tests to lunar conditions
- Create virtual training environments
- Plan future lunar surface operations
- Interpret new lunar soil test data
- Extensible to planetary surface operations

Examples of Large Deformation and Progressive Failure





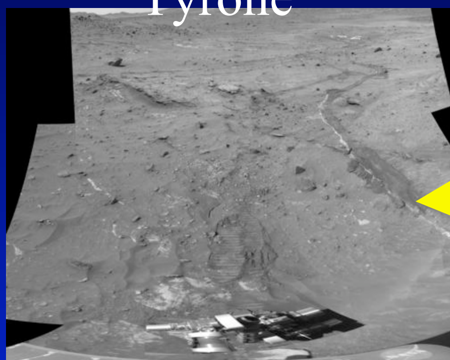
Inchworm mobility

Approach

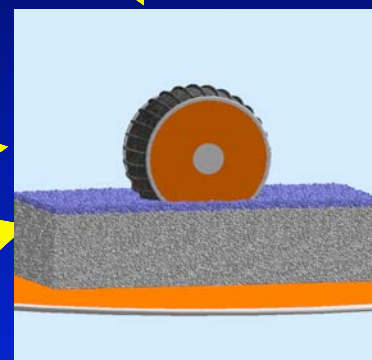
- Conduct physical experiments to guide model development and validate simulation accuracy
- Physical experiments
  - Mobility - inchworm & traditional
  - Excavation - static & percussive
  - Geotech. Properties - micromechanical, triaxial & penetrometer
- DEM model development
  - Parallel supercomputer based
  - Maximize algorithm efficiency
  - Incorporate realistic particle shape & contact physics
  - Maximize scalability

How to Develop a Physical DEM

MER Spirit tracks and disturbed soil near Tyrone

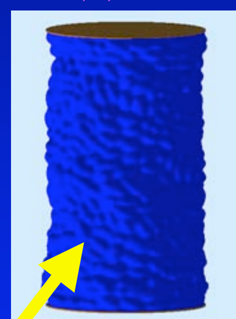


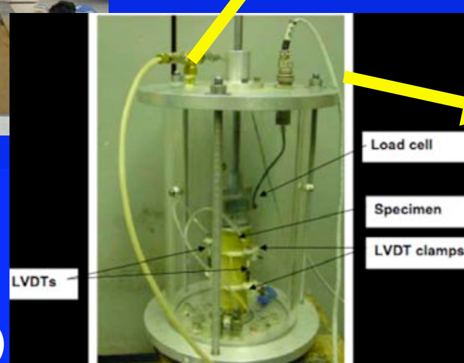
DEM Soil Parameters



Rover wheel test in layered soil (German Aerospace Center)

Rover wheel laboratory experiment (Cornell)

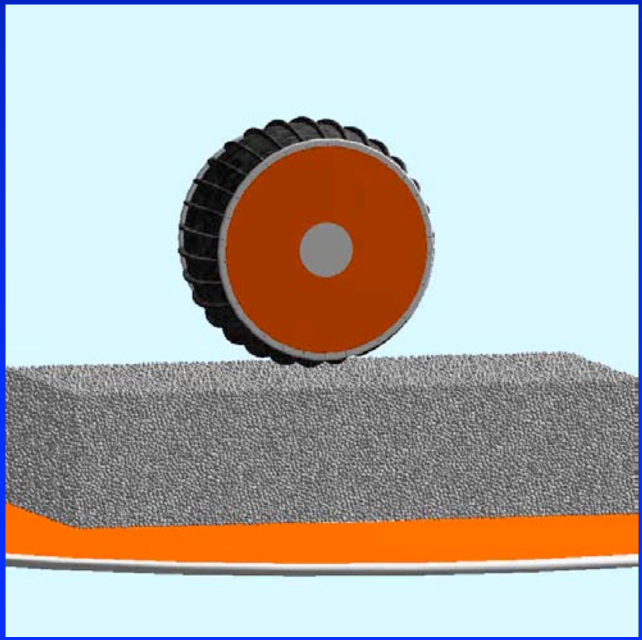


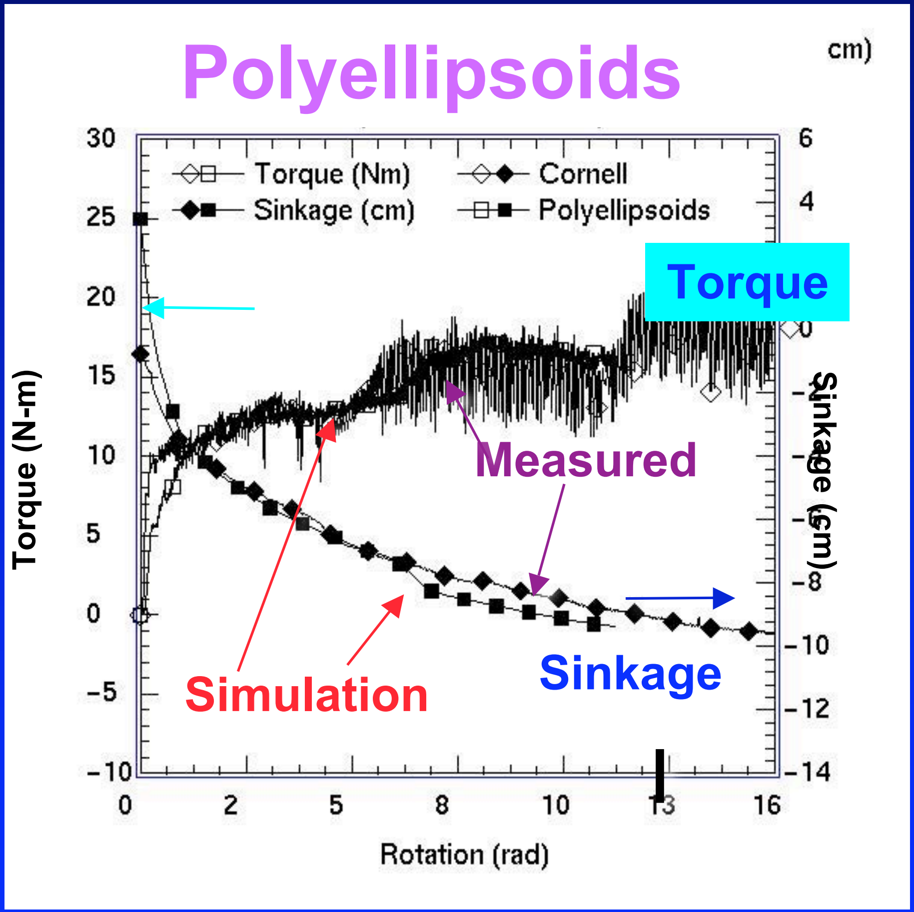


Continuum Soil Properties

1. **Soil geotechnical properties**
2. **Machine/soil interaction model parameters**
3. **Soil layer structure & properties**

MER Wheel Test and Simulation

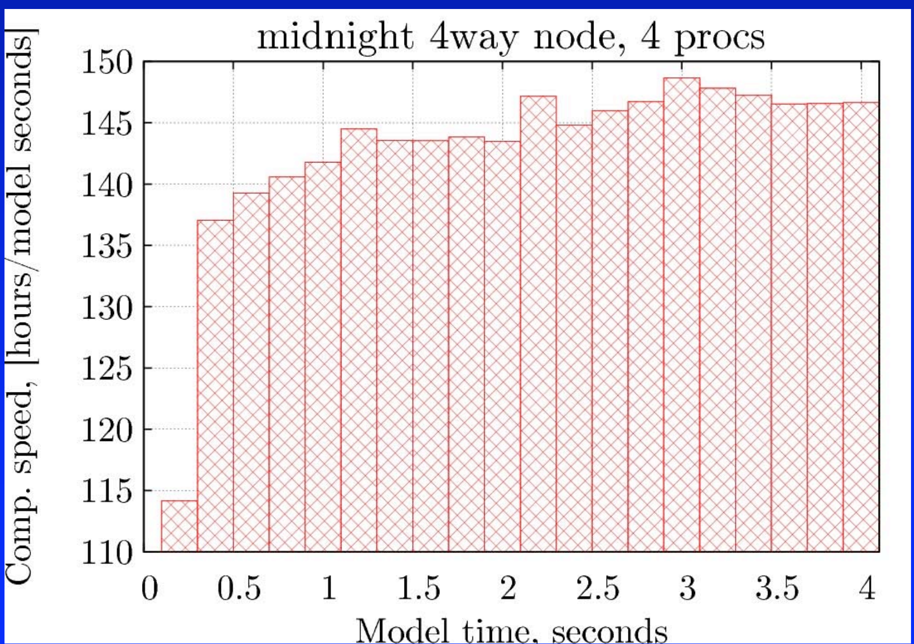




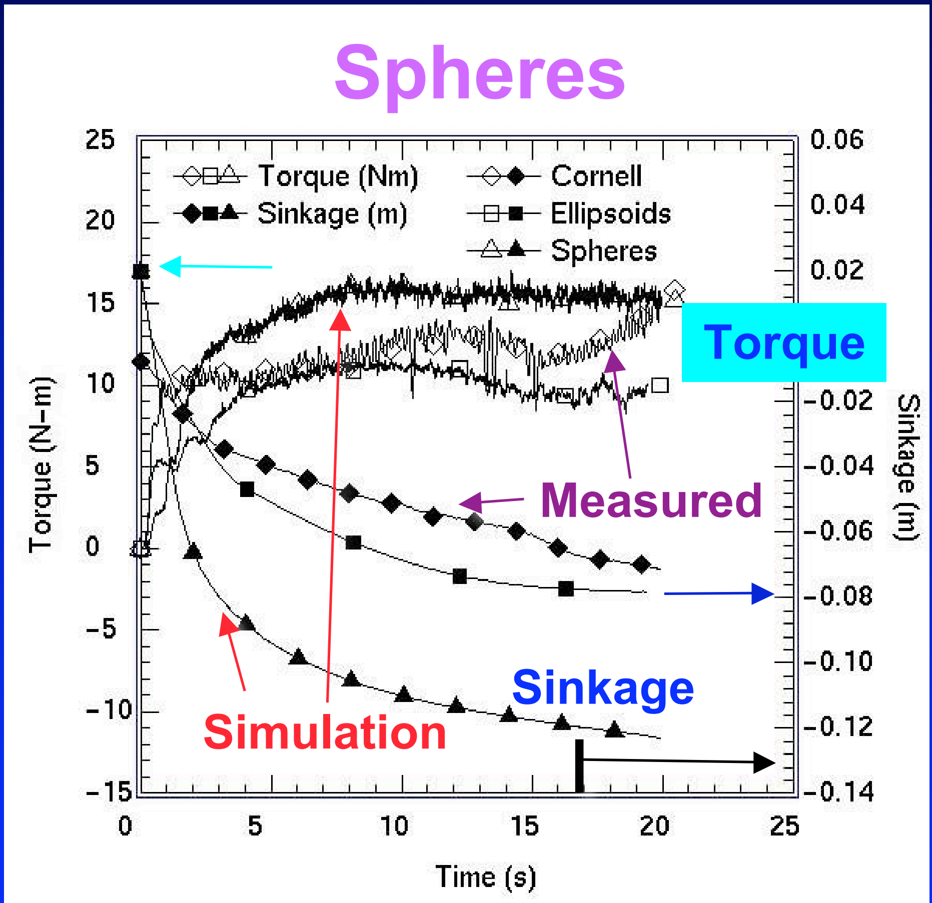
Simulation accuracy: Polyellipsoids

Challenges

- Particle properties affect accuracy
- Increased particle complexity increases computational burden

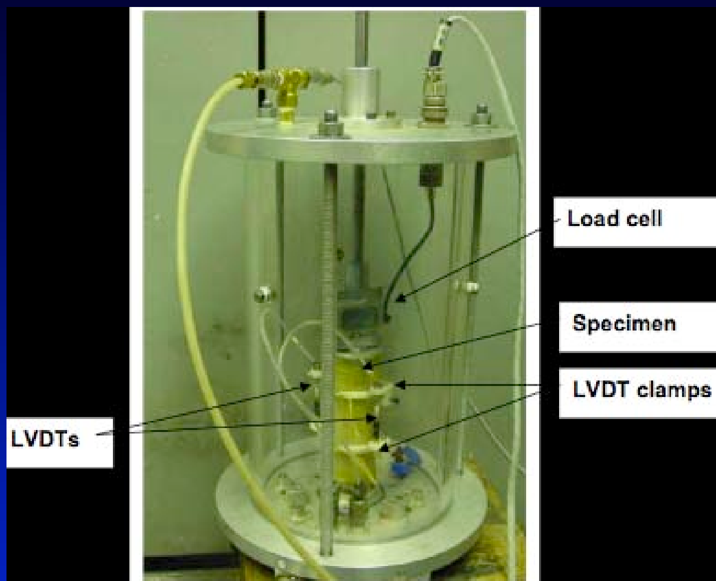


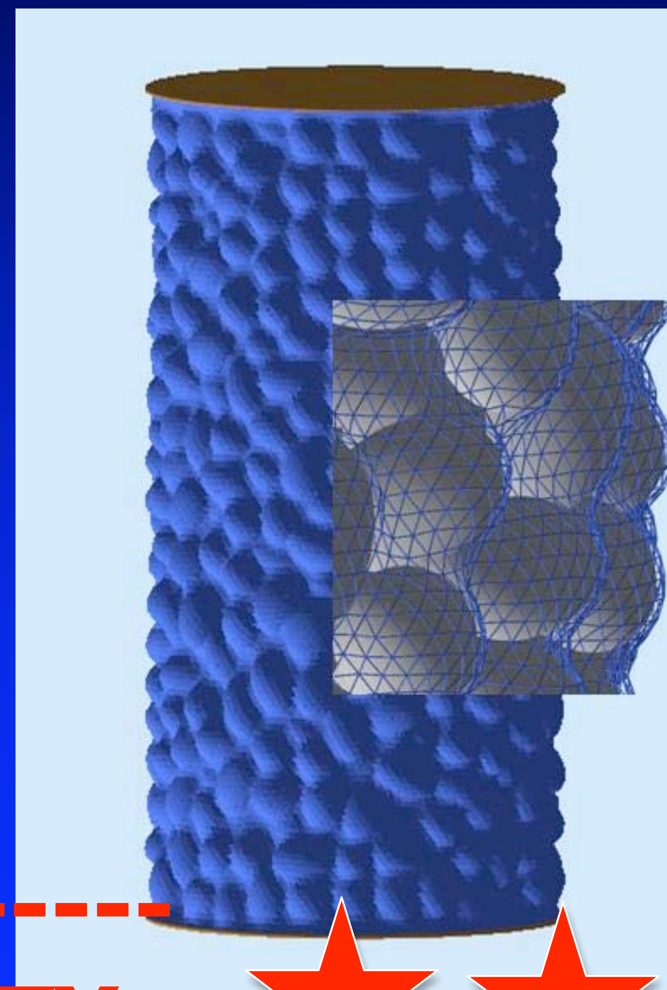
Speed of original DEM code (hours/model seconds)



Simulation accuracy: Spheres

Triaxial Methods

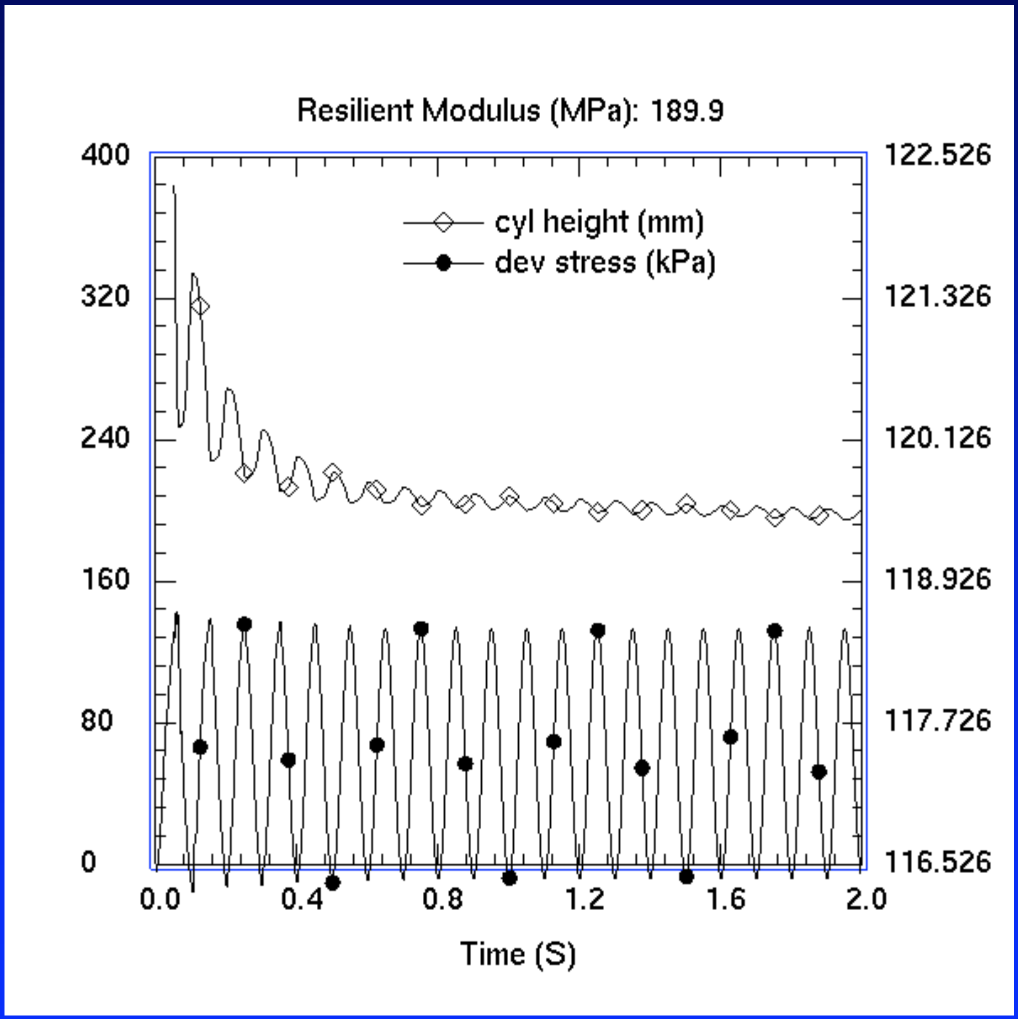




Vicksburg sand - Polyellipsoids

LEVEL OF DIFFICULTY =

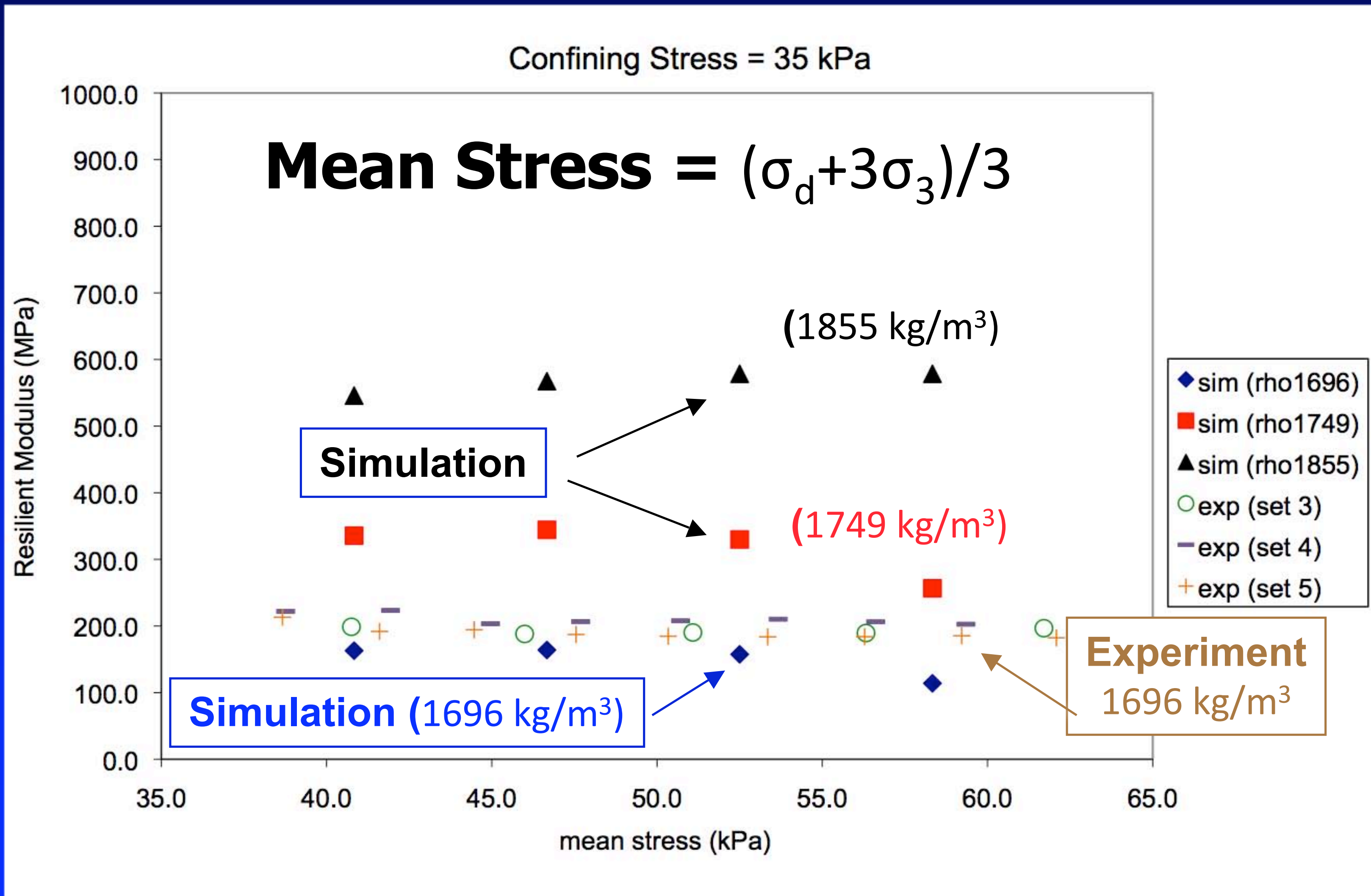
Resilient Modulus Test



$$E_R = \sigma_d/\varepsilon$$

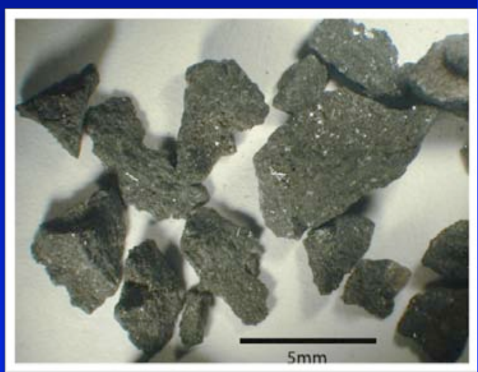
- Density = 1696 kg/m^3
- Confining Stress,
  σ_3 = 70 kPa
- Deviatoric Stress,
  σ_d = 140 kPa

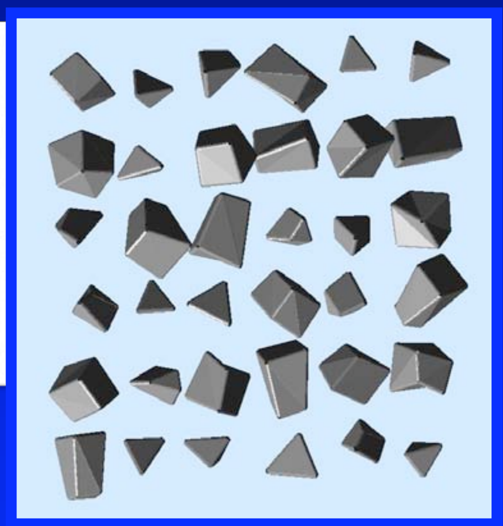
Resilient Experiment Versus Simulation

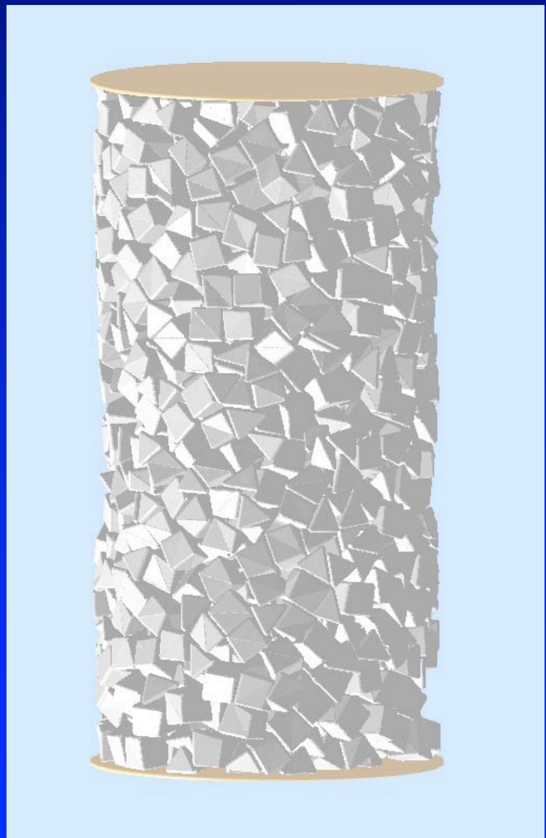


Complex Particle Shapes JSC – 1a

LEVEL OF DIFFICULTY =







- complex angular shapes

Polyhedra?

Status

- Completed, in-progress, or in-development physical experiments
  - Mobility - inching & traditional
  - Excavation - static and percussive
  - Geotech. Properties - micromechanical, triaxial &
  - penetrometer
- Completed or in-progress DEM model efforts
  - Improved algorithms & architecture of DEM code
  - New DEM code operational for spherical particles on 8 processor shared memory node
  - Simulation of triaxial tests
  - Improved Rover wheel digging simulation
- Planned DEM model efforts
  - Simulation of physical tests
  - Add complex particle shapes/ properties
  - Develop distributed memory capability to increase scalability

Sources of Support

- NASA- Lunar Science Institute
- Alaska Region Supercomputing Center
- USACE-ERDC
- NASA-MFRP
- NASA-LASER
- NASA-MER
- NASA-KSC